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The Chemical Composition of Olivine-Bronzite and Olivine-Hypersthene Chondrites

By Brian Mason[1]

INTRODUCTION

The olivine-bronzite and olivine-hypersthene chondrites comprise about 95 per cent of all chondrites, the remaining groups (enstatite, olivine-pigeonite, and carbonaceous chondrites) each having comparatively few representatives (Mason, 1962). These two major classes (hereinafter referred to together as the common chondrites), although very similar in elemental composition, show some significant differences, the most prominent being that total iron in the olivine-bronzite chondrites is about 6 per cent greater than in the olivine-hypersthene chondrites. This fact was clearly established by the work of Urey and Craig (1953), who on this basis divided all chondrites into two groups, the L (low-iron), and H (high-iron) groups. Craig (1964) restricted these groups to the olivine-hypersthene and olivine-bronzite chondrites, divided off a few olivine-hypersthene chondrites as a distinct group, which he called soko-banjites, and recognized the enstatite chondrites and carbonaceous chondrites as separate entities.

EVALUATION OF CHEMICAL ANALYSIS

The basis of the Urey-Craig classification was their careful evaluation

[1] United States National Museum, Smithsonian Institution, Washington, D. C.; formerly Chairman, Department of Mineralogy, the American Museum of Natural History.

of all published chondrite analyses, some 286 in all. From these analyses Urey and Craig were faced with the problem of attempting to select the more trustworthy analyses and to eliminate the bad. In their own words: "We have adopted the following standards for eliminating analyses from our lists. Analyses are discarded when the alkalies have not been determined or found, when K_2O is greater than Na_2O, when $Na_2O + K_2O$ is greater than 3%, when CaO or Al_2O_3 is lacking, or present in extremely small amounts, when CaO is greater than about 4% or Al_2O_3 is greater than about 5%, when S is lacking or very low, or very high except in the analyses of the enstatite chondrites which are generally characterized by a high sulphur content, and when Cr_2O_3 or MnO is much greater than about 1%." They also eliminated analyses showing large amounts of H_2O, Fe_2O_3, and NiO, arguing that the presence of these components indicated decomposition by weathering (this criterion eliminated not only weathered meteorites but also the carbonaceous chondrites, which, however, are not considered in this discussion). On the basis of the above criteria Urey and Craig eliminated 192 analyses and selected 94 "superior" analyses, on which they based their discussion and conclusions.

Few would quarrel with the criteria used by Urey and Craig to eliminate unsatisfactory analyses. Indeed, in the light of further research over the past decade, much of it stimulated by their pioneer work, it can be seen that their further comment—"We have undoubtedly included some incorrect analyses since we have at all times tried to err on the side of keeping too many rather than exclude any analyses that might be correct"—is undoubtedly true. In view of this, and in view of the considerable number of new analyses that have been published since 1953, a re-examination of the situation seems worthwhile.

The evaluation of chemical analyses has been thoroughly discussed by Washington (1917), who was faced with a similar problem—the selection of the "superior" analyses from some 8600 analyses of igneous rocks published from 1884 to 1913. He based his evaluation on accuracy and completeness. The principal criteria for accuracy were (1) agreement with the mineralogical composition, and (2) summation close to 100. Completeness, i.e., determination of all components present in more than trace amounts (in practice, in amounts greater than about 0.1%), was judged largely from a knowledge of the mineralogical composition, which would indicate the possible presence of unusual components. On these criteria he established a rating system, whereby each analysis was classified, as follows:

I: First rate or excellent
II: Second rate or good
III: Third rate or fair
IV: Fourth rate or poor
V: Fifth rate or bad

Those analyses receiving a rating I, II, or III were considered "superior"; those rated IV or V, "poor." It seems that a rating system for meteorite analyses can now be evolved which would enable a more precise evaluation than that provided by Urey and Craig. With this in mind the following criteria are suggested:

SUMMATION: Washington established the following grades for accuracy based on summation:

A: 99.50–100.75
B: 99.00–99.50; 100.75–101.25
C: 98.50–99.00; 101.25–101.75
D: <98.50; >101.75

He commented: "Figures which do not fall within these limits (A, 99.50–100.75) are good evidence of error; however, summations within these limits are not necessarily proof of good results. . . . Summations somewhat above or below the limits fixed are excusable in analyses of complex minerals or of meteorites." Washington's grading by summation may reasonably be applied to analyses of olivine-bronzite and olivine-hypersthene chondrites; this grading is not strictly applicable to the evaluating of analyses of enstatite and carbonaceous chondrites, which contain some elements in combinations not readily determined by standard analytical techniques.

AGREEMENT WITH MINERALOGICAL COMPOSITION: A cross check that has been insufficiently used is the correlation that must exist between the mineralogical composition of a chondrite and its chemical analysis. A number of criteria may be established on this basis, since the mineralogy of the olivine-bronzite and olivine-hypersthene chondrites is remarkably uniform. The approximate range for the essential minerals, in weight per cent, is:

Olivine, $(Mg,Fe)_2SiO_4$	30–53
Orthopyroxene, $(Mg,Fe)SiO_3$	25–35
Plagioclase, $(Na,Ca)(Al,Si)_4O_8$	5–10
Nickel-iron, (Ni,Fe)	1–20
Troilite, FeS	4–7

A consequence of this uniformity in mineralogical composition is that we may reasonably expect a marked uniformity in the chemical analyses of these meteorites, without extreme variation in the individual compo-

nents, except for Fe and FeO, which within each group show a generally inverse relationship.

A significant evaluation of the accuracy of the analysis can be established by a comparison of the FeO/FeO+MgO mole per cent given by the analysis, and the corresponding figure for the olivine. Essentially all the FeO and MgO in the meteorite are combined in olivine and orthopyroxene, and the FeO/FeO+MgO percentages in the co-existing olivine and orthopyroxene in an individual chondrite are very similar, the percentage for olivine usually being somewhat greater than that for pyroxene. This percentage can readily be determined for olivine by measurement of refractive indices (Ringwood, 1961), by X-ray diffraction (Mason, 1963), or by electron microprobe analysis (Keil and Fredriksson, 1964).[1]

If the difference between the FeO/FeO+MgO mole percentage from the analysis and that determined on the olivine deviates by more than ± 3, the discrepancy is serious.

Another critical test of the accuracy of a chemical analysis of a chondrite is the relationship between Al_2O_3 and $Na_2O(+K_2O)$. The only major phrase in which Na_2O and K_2O are combined is feldspar, in which the molecular proportion $Na_2O+K_2O:Al_2O_3$ is 1:1. Therefore, if the amount of Al_2O_3 in an analysis is insufficient to combine with all the Na_2O and K_2O to form feldspar, the fact is prime evidence that either the Al_2O_3 has been underestimated or the $Na_2O + K_2O$ overestimated. In either case, the analysis is suspect, for these components at least.

COMPLETENESS: A complete analysis of a common chondrite, with completeness as requiring the determination of all components present in amounts greater than 0.1 per cent, demands the determination of the following components: SiO_2, MgO, FeO, Al_2O_3, CaO, Na_2O, Cr_2O_3, P_2O_5, MnO, TiO_2, K_2O, FeS, Fe, and Ni; Co is normally determined, although the amount is usually somewhat less than 0.1 per cent. Many analyses fail to report one or more of the components Cr_2O_3, P_2O_5, MnO, TiO_2, K_2O, and to that extent are unsatisfactory.

[1] In this connection it is necessary to consider the accuracy and precision of the physical methods for determining FeO/FeO+MgO mole percentage in olivine. Mason (1963) claimed an accuracy of ± 1 for this figure, which Keil and Fredriksson (1964) disputed, suggesting a possible error of 10 per cent (i.e., ± 2 in the figure for an FeO/FeO+MgO mole percentage of 20). Keil and Fredriksson claim an accuracy of ± 0.3 per cent Fe and Mg (equivalent to approximately ± 1 in FeO/FeO+MgO mole percentage) for their microprobe analyses. Mason's figures are consistently 1–2 per cent higher for FeO/FeO+MgO in olivine than those for the same meteorites by Keil and Fredriksson. It seems plausible that the true value lies between these two results, i.e., Mason's figures are consistently a little higher than the true values, whereas those of Keil and Fredriksson are a little lower.

Another criterion that may well be used in the selection of analyses for statistical computations is whether the meteorite was an observed fall, or whether it was a find. Most finds are weathered, and the immediate effect of weathering is to diminish the amount of free iron and increase the amount of iron oxides; weathering also has more subtle effects, as Moore and Brown (1963) have shown in the marked difference in barium content between falls and finds.

Many other criteria might be used in the evaluation of chemical analyses of chondrites, but those discussed above should be adequate for at least an initial screening of the available analyses. On the bases, therefore, of these criteria, the following rating system has been evolved:

		Rating
A. Accuracy		
(F^1 olivine) — (F analysis) =	±0–2	1
	±3–4	2
	±5–6	3
	±7–10	4
	>10	5
Na_2O+K_2O (molecular)>Al_2O_3 (molecular)		1
B. Summation		
99.50–100.75		0
99.00–99.49; 100.76–101.25		1
98.50–98.99; 101.26–101.75		2
<98.50; >101.75		3
C. Completeness:		
Cr_2O_3 not determined		1
P_2O_5 not determined		1
MnO not determined		1
TiO_2 not determined		1
K_2O not determined		1
D. Analyses of finds are not considered		

By adding up these ratings for each individual analysis, we obtain an over-all rating, and presumably the quality of the analysis is reflected by the inverse of the rating total. This rating system is applied in table 1 to the "superior" analyses selected by Urey and Craig (1953), and in table 2 to analyses published since 1953, plus a few rejected by them on what may have been inadequate grounds. A high-rating figure certainly indicates an unsatisfactory analysis; unfortunately, a low figure is no guarantee of accuracy. For example, the analysis by Kokta of Knyahinya (no. 36, table 1), is rated 3, but a re-analysis of this meteorite (no. 135, table 2) shows that Kokta's analysis is completely erroneous for many components. Kokta's analyses have not been used in the following

[1] F = FeO/FeO+MgO (mole per cent).

TABLE 1

RATING OF ANALYSES CLASSED AS "SUPERIOR" BY UREY AND CRAIG (1953)

		Fanal	Fol	Comments	Rating
1	Albareto	25	27	No P_2O_5; no TiO_2	3
2	Allegan	18	19		1
3	Baroti	25	25	No MnO	2
4	Beaver Creek	19	19		1
5	Benld	21	20		1
6	Benoni	19	20		1
7	Bjurbole	22	26		2
8	Bowden	20	18	Find	
9	Cape Girardeau	21	19	No MnO, TiO_2	3
10	Chandakapur	34	24	No P_2O_5	6
11	Chantonnay	25	23	Sum 97.79; no P_2O_5, TiO_2, K_2O	7
12	Cobija	21	19	Find	
13	Collescipoli	12	19	Sum 99.48; no P_2O_5	6
14	Coon Butte	25	24	Find	
15	Cronstad	16	18	Sum 99.41	2
16	Crumlin	23	24		1
17	Daniel's Kuil			Enstatite chondrite	
18	Djati-Pengilon	27	20	Sum 99.06; no P_2O_5, MnO, TiO_2	8
19	Ekeby	21	19	Sum 99.37	2
20	Elsinora	17	17	Find	
21	Estacado	24	19	Find	
22	Forest City	16	19	Sum 99.39; no P_2O_5, MnO, TiO_2	6
23	Forksville	28	26	Sum 99.09; no MnO, TiO_2	4
24	Girgenti	28	25	$Na_2O > Al_2O_3$; no P_2O_5, MnO, TiO_2, K_2O	7
25	Gnadenfrei	33	18	No P_2O_5, MnO, TiO_2, K_2O	9
26	Gopalpur	25	20	Sum 98.91; no Cr_2O_3, P_2O_5, TiO_2	7
27	Grossliebenthal	24	25	Sum 99.34; No TiO_2, $Na_2O+K_2O > Al_2O_3$	4
28	Hendersonville	18	24	Find	
29	Hessle	21	19	Sum 100.84; no P_2O_5, TiO_2, K_2O	5
30	Homestead	22	24	No TiO_2	2
31	Hvittis			Enstatite chondrite	
32	Kernouve	22	18	Sum 100.77; no Cr_2O_3, P_2O_5, MnO, TiO_2, K_2O	8
33	Khairpur			Enstatite chondrite	
34	Khetri	20	18	Sum 101.20; no P_2O_5, MnO, TiO_2, K_2O	6
35	Kimble County	27	19	Find	
36	Knyahinya	19	25		3
37	Lanzenkirchen	23			
38	Launton	23	23		1
39	Lesves	28	25	Sum 101.15; no P_2O_5, MnO, TiO_2	6
40	Limerick	16	19	$Na_2O+K_2O > Al_2O_3$	3
41	Linum	3	23	No P_2O_5	6

TABLE 1—*(Continued)*

		Fanal	Fol	Comments	Rating
42	Lissa	26	23	$Na_2O+K_2O>Al_2O_3$	3
43	Lundsgard	26	24	$Na_2O+K_2O>Al_2O_3$	2
44	Mauerkirchen	40	24	No P_2O_5, MnO, TiO_2	8
45	McKinney	23	24	Find	
46	Merua	15	18		2
47	Meuselbach	27	24	Sum 100.99; no P_2O_5, MnO, TiO_2, K_2O	7
48	Mezel	26	24	Sum 98.67; no K_2O	4
49	Mezo-Madaras	26	26	No P_2O_5, TiO_2, K_2O	4
50	Modoc	21	23	Sum 98.71; no Cr_2O_3, P_2O_5, TiO_2	6
51	Moorleah	24	23	No Cr_2O_3, P_2O_5, MnO, TiO_2	5
52	Mount Browne	23	17	No P_2O_5, MnO, TiO_2	6
53	Narellan	30	25	Sum 99.16	4
54	Oakley	20	21	Find	
55	Oesede	16			
56	Ojuelos Altos	20	25	Sum 99.47; no Cr_2O_3, MnO, TiO_2	7
57	Olivenza	32	30	No TiO_2	2
58	Olmedilla de Alarcon	18	18	No TiO_2	2
59	Orvinio	16	23	Sum 101.16; no Cr_2O_3, P_2O_5, MnO, TiO_2	9
60	Oubari	31	26	Find	
61	Perpeti	25	25	$Na_2O + K_2O > Al_2O_3$	2
62	Phu-Hong	22	18	No TiO_2	3
63	Phuoc-Binh	24			
64	Plantersville	22	20	No TiO_2	2
65	Prambachkirchen	23			
66	Rakovka	24	24	Sum 99.25; no P_2O_5, TiO_2; $Na_2O + K_2O > Al_2O_3$	5
67	Rangala	25	25		1
68	Rich Mountain	19	24	Sum 96.39; no Cr_2O_3, MnO, TiO_2	9
69	Rosebud	29	19	Find	
70	Saint Christophe	23	25	No P_2O_5, MnO, TiO_2	4
71	Saint Denis-Westrem	26	25	Sum 101.63; no P_2O_5, MnO, TiO_2	6
72	Saint Michel	23	24	No P_2O_5	2
73	Saint-Sauveur			Enstatite chondrite	
74	Salt Lake City	22	19	Find	
75	Saratov	23	24		1
76	Sazovice	26			
77	Seldebourak	25	19	$Na_2O+K_2O>Al_2O_3$	4
78	Shelburne	24	24	Sum 99.37; no P_2O_5, TiO_2	4
79	Soko-Banja	28	27		1
80	Stalldalen	16	19	Sum 99.47; no TiO_2	4
81	Strathmore	23	25		1
82	Suwahib	21	14	Find	
83	Tabor	21	18		2
84	Tanezrouft	19	20	Find	

TABLE 1—*(Continued)*

		Fanal	Fol	Comments	Rating
85	Tieschitz	35		Olivine-pigeonite chondrite	
86	Tourinnes-la-Grosse	25	25	$Na_2O+K_2O>Al_2O_3$; no P_2O_5, MnO, TiO_2	4
87	Tuan Tuc	25	24	No TiO_2	2
88	Varpaisjarvi	23	25	Find	
89	Vavilovka	29	30	$Na_2O+K_2O>Al_2O_3$; Sum 99.18; no P_2O_5, TiO_2	4
90	Warbreccan	24	24		1
91	Warrenton	37		Olivine-pigeonite chondrite	
92	Wittekrantz	25	23		1
93	Zebrak	22	18		2
94	Zemaitkiemis	23	24	$Na_2O+K_2O>Al_2O_3$; no Cr_2O_3	4

TABLE 2

RATING OF ADDITIONAL ANALYSES

		Fanal	Fol	Comments	Rating
101	Aarhus	15	18	$Na_2O+K_2O>Al_2O_3$	3
102	Alexandrovsky	13	18	$Na_2O+K_2O>Al_2O_3$	4
103	Appley Bridge	32	29		2
104	Bogoslovka	15	19	Find	
105	Breitscheid	15	19		2
106	Bruderheim	23	24		1
107	Bruderheim	24	24		1
108	Bruderheim	23	24		1
109	Chateau-Renard	22	25		2
110	Demina	22	23		1
111	Douar Mghila	29	30		1
112	Elenovka	25	25		1
113	Ensisheim	29	28	No TiO_2	2
114	Estacado	23	19	Find	
115	Farmington	26	24	Sum 99.27	2
116	Forest City	19	19		1
117	Fukutomi	21	24		2
118	Fukutomi	21	24	Sum 99.20	3
119	Geidam	22	19	Sum 99.24	3
120	Gifu	25	25		1
121	Glasatovo	17	18	Sum 98.57	3
122	Guidder	25	29		2
123	Hainaut	21	19		1
124	Hamlet	27	27		1
125	Harleton	25	26		1
126	Holbrook	21	25		2

TABLE 2—*(Continued)*

		Fanal	Fol	Comments	Rating
127	Idutywa	20	19		1
128	Isoulane	30	25	Find	
129	Kainsaz	15			
130	Kaptal-Aryk	20	23	Sum 98.61	4
131	Kasamatsu	18	22		2
132	Kesen	19	17		1
133	Khmelevka	24	23		1
134	Kissij	14	17	Find	
135	Knyahinya	27	25		1
136	Krasnoi-Ugol	24	24	Sum 100.79	2
137	Kulp	20	18	Sum 100.82	2
138	Kunashak	22	24		1
139	Kunashak	23	24	Sum 98.88	3
140	Kunashak	23	24	Sum 99.48	2
141	Kunashak	20	24	Sum 97.84	6
142	Kuznetzovo	23	23		1
143	Kyushu	22	26		2
144	Lake Brown	25	25	Find	
145	Leedey	23	24		1
146	Leedey	27	24	Sum 101.05	3
147	Linum	25	23	Sum 99.13	2
148	Manbhoom	30	30		1
149	Mangwendi	32	29		2
150	Manych	22		Sum 101.00	
151	McKinney	26	24	Find	
152	Mern	20	24	$Na_2O+K_2O>Al_2O_3$	3
153	Miller	10	19	Sum 99.46	5
154	Mocs	21	24	Sum 99.48	3
155	Monte das Fortes	22	24		1
156	Näs	29	30	Find	
157	New Concord	21	24	Sum 99.14	3
158	Nikolaevka	15	19	Sum 100.97	3
159	Nikolskoe	26	24	$Na_2O+K_2O>Al_2O_3$	2
160	Oakley	20	21	Find	
161	Ochansk	16	20		2
162	Ochansk	14	20		3
163	Orlovka	21	19	Find	
164	Ottawa	29	29	Sum 101.01	2
165	Pantar	21	18		2
166	Pantar	21	18		2
167	Pantar	17	18		1
168	Paragould	28	25		2
169	Paragould	28	25		2
170	Paragould	28	25		2
171	Pavlograd	24	25	Sum 98.69	3

TABLE 2—*(Continued)*

		Fanal	Fol	Comments	Rating
172	Pervomaisky	21	24		2
173	Pervomaisky	23	24		1
174	Petropavlovka	15	16	Find	
175	Pultusk	18	18	Sum 98.91	3
176	Richardton	20	19		1
177	Saratov	21	24		2
178	Sasagase	19	20		1
179	Savtschenskoje	25	28	Sum 100.76	3
180	Selma	27	20	Find	
181	Sevrukovo	22	25		2
182	Sinnai	19	24	Sum 99.05	4
183	Slobodka	25	23		1
184	Sone	19	21		1
185	Sungach	20	18	Sum 99.19	2
186	Tarbagatai	22	23	Find	
187	Tomhannock Creek	26	18	Find	
188	Tomita	23	23		1
189	Tromoy	16	18		1
190	Vavilovka	29	30	Sum 101.14	2
191	Vengerovo	18	19	Sum 97.11; no P_2O_5	4
192	Yonozu	19	18		1
193	Zavetnoe	24	24		1
194	Zhovtnevyi	18	19	Sum 100.91	2

References

101 Mat. Fys. Medd. Danske Vid. Selsk., vol. 34, p. 17, 1964
102 Meteoritika, no. 21, p. 54, 1961
103 Geochim. Acta, vol. 28, p. 533, 1964
104 Meteoritika, no. 21, p. 54, 1961
105 Geochim. Acta, vol. 17, p. 320, 1959
106 Jour. Geophys. Res., vol. 66, p. 3574, 1961
107 Jour. Geophys. Res., vol. 66, p. 3557, 1961
108 Geochim. Acta, vol. 28, p. 1697, 1964
109 Amer. Mus. Novitates, no. 2069, p. 9, 1961
110 Meteoritika, no. 21, p. 54, 1961
111 Notes Mem. Serv. Geol. Maroc, vol. 5, p. 201, 1951
112 Geol. Jour. (Ukraine), vol. 13, p. 80, 1953
113 Min. Mag., vol. 19, p. 163, 1921
114 Amer. Mus. Novitates, no. 2154, p. 10, 1963
115 Wiik, unpublished
116 Amer. Mus. Novitates, no. 2220, p. 5, 1965
117 Miyashiro, unpublished
118 Miyashiro, unpublished
119 Amer. Mus. Novitates, no. 2220, p. 16, 1965

TABLE 2—*(Continued)*

120 Japanese Jour. Geol. Geogr., vol. 33, p. 128, 1962
121 Meteoritika, no. 21, p. 54, 1961
122 Geochim. Acta, vol. 4, p. 83, 1953
123 Geochim. Acta, vol. 9, p. 280, 1956
124 Wiik, unpublished
125 Clarke, unpublished
126 Geochim. Acta, vol. 21, p. 279, 1961
127 South African Jour. Sci., vol. 53, p. 73, 1956
128 Compt. Rend. Acad. Sci., Paris, vol. 242, p. 2369, 1956
129 Meteoritika, no. 25, p. 130, 1964
130 Meteoritika, no. 21, p. 54, 1961
131 Japanese Jour. Geol. Geogr., vol. 34, p. 195, 1963
132 Japanese Jour. Geol. Geogr., vol. 33, p. 76, 1962
133 Meteoritika, no. 25, p. 130, 1964
134 Meteoritika, no. 25, p. 130, 1964
135 Amer. Mus. Novitates, no. 2154, p. 14, 1963
136 Meteoritika, no. 21, p. 54, 1961
137 Meteoritika, no. 25, p. 130, 1964
138 Meteoritika, no. 10, p. 42, 1952
139 Meteoritika, no. 10, p. 42, 1952
140 Meteoritika, no. 21, p. 54, 1961
141 Meteoritika, no. 21, p. 54, 1961
142 Meteoritika, no. 21, p. 54, 1961
143 Geochim. Acta, vol. 21, p. 274, 1961
144 Min. Mag., vol. 22, p. 155, 1929
145 Geochim. Acta, vol. 28, p. 1697, 1964
146 Wiik, unpublished
147 Geochim. Acta, vol. 9, p. 280, 1956
148 Geochim. Acta, vol. 28, p. 533, 1964
149 Min. Mag., vol. 24, p. 1, 1935
150 Meteoritika, no. 25, p. 130, 1964
151 Maynes, unpublished
152 Geochim. Acta, vol. 9, p. 280, 1956
153 Geochim. Acta, vol. 21, p. 269, 1961
154 Amer. Mus. Novitates, no. 2069, p. 17, 1961
155 Geochim. Acta, vol. 9, p. 280, 1956
156 Geochim. Acta, vol. 28, p. 533, 1964
157 Amer. Mus. Novitates, no. 2069, p. 22, 1961
158 Meteoritika, no. 21, p. 54, 1961
159 Meteoritika, no. 18, p. 66, 1959
160 Geochim. Acta, vol. 9, p. 280, 1956
161 Meteoritika, no. 18, p. 66, 1959
162 Geochim. Acta, vol. 9, p. 280, 1956
163 Meteoritika, no. 18, p. 66, 1959
164 Amer. Mus. Novitates, no. 2069, p. 5, 1961
165 Geochim. Acta, vol. 28, p. 1398, 1964
166 Geochim. Acta, vol. 28, p. 1398, 1964
167 Maynes, unpublished

TABLE 2—*(Continued)*

168	Fieldiana, vol. 10, p. 295, 1955
169	Fieldiana, vol. 10, p. 295, 1955
170	Fieldiana, vol. 10, p. 295, 1955
171	Meteoritika, no. 18, p. 66, 1959
172	Meteoritika, no. 21, p. 54, 1961
173	Meteoritika, no. 21, p. 54, 1961
174	Meteoritika, no. 18, p. 66, 1959
175	Meteoritika, no. 21, p. 54, 1961
176	Amer. Mus. Novitates, no. 2154, p. 4, 1963
177	Meteoritika, no. 22, p. 72, 1962
178	Japanese Jour. Geol. Geogr., vol. 33, p. 241, 1962
179	Meteoritika, no. 21, p. 54, 1961
180	Amer. Mus. Novitates, no. 2010, p. 5, 1960
181	Meteoritika, no. 18, p. 66, 1959
182	Period. Mih. Roma, vol. 27, p. 179, 1959
183	Meteoritika, no. 21, p. 54, 1961
184	Bull. Nat. Sci. Mus. Tokyo, vol. 6, p. 354, 1963
185	Meteoritika, no. 25, p. 130, 1964
186	Meteoritika, no. 21, p. 54, 1961
187	Min. Mag., vol. 32, p. 533, 1960
188	Japanese Jour. Geol. Geogr., vol. 34, p. 65, 1963
189	Geochim. Acta, vol. 9, p. 280, 1956
190	Meteoritika, no. 21, p. 54, 1961
191	Meteoritika, no. 11, p. 99, 1954
192	Jour. Fac. Sci. Tokyo, vol. 14, p. 447, 1963
193	Meteoritika, no. 18, p. 66, 1959
194	Meteoritika, no. 18, p. 66, 1959

compilations. However, a statistical analysis of the most highly rated analyses (those rated 1, 2, 3) shows clearly the permissible variability of the individual components.

The means of the selected analyses (those rated 1, 2, or 3) are given in table 3, along with the means calculated previously by Urey and Craig (1953) and Craig (1964). Craig selected his analyses in a way quite different from that followed in this paper, and the close correspondence of the two sets of figures begets confidence in their actually providing adequate mean compositions for these two important groups of meteorites. The individual components are here discussed in detail.

SiO_2: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 34.27 per cent (analysis 176) to 37.93 per cent (analysis 4), and the mean is 36.33 per cent (fig. 1). For the olivine-hypersthene chondrites the range is from 38.23 per cent (analysis 43) to 41.73 per cent (analysis 122) and the mean 39.87 per cent (fig. 2). Vogt and Ehmann (in press) have made direct determinations of silicon

TABLE 3

MEANS OF ANALYSES OF OLIVINE-BRONZITE AND OLIVINE-HYPERSTHENE CHONDRITES
(1, Urey and Craig, 1953; 2, Craig, 1964; 3, the present paper. The figures in parentheses are the numbers of analyses used in the calculation of the mean.)

	Olivine-Bronzite Chondrites			Olivine-Hypersthene Chondrites		
	1 (41)	2 (27)	3 (36)	1 (53)	2 (30)	3 (68)
SiO_2	36.17	36.52	36.33	39.49	39.88	39.87
MgO	22.93	23.48	23.53	24.55	24.98	25.16
FeO	9.26	8.87	9.61	14.97	13.12	14.66
Al_2O_3	2.36	2.43	2.66	2.66	2.31	2.51
CaO	1.95	1.82	1.76	1.96	1.90	1.89
Na_2O	0.91	0.85	0.86	1.04	0.88	0.95
K_2O	0.17	0.14	0.12	0.18	0.14	0.15
Cr_2O_3	0.27	0.36	0.42	0.43	0.44	0.45
MnO	0.23	0.25	0.25	0.27	0.27	0.29
TiO_2	0.11	0.13	0.15	0.11	0.15	0.15
P_2O_5	0.17	0.23	0.26	0.24	0.26	0.27
Silicate	74.53	75.08	75.95	85.85	84.33	86.35
Fe	17.76	17.23	16.79	7.04	7.70	6.28
Ni	1.68	1.58	1.63	1.06	1.12	1.10
Co	0.10	0.085	0.089	0.07	0.059	0.059
Metal	19.54	18.90	18.51	8.17	8.88	7.44
Fe	3.62	3.40	3.35	3.66	3.92	3.86
S	2.07	1.95	1.92	2.11	2.25	2.21
FeS	5.69	5.35	5.27	5.77	6.17	6.07
Sum	100.06[a]	99.74[b]	99.73	100.07[c]	99.79[d]	99.86
Total Fe	28.58	27.52	27.61	22.33	21.82	21.53

[a] Includes P, 0.05; and H_2O, 0.25.
[b] Includes C, 0.07; Cu, 0.012; and H_2O, 0.33.
[c] Includes P, 0.04; and H_2O, 0.24.
[d] Includes C, 0.03; Cu, 0.010; and H_2O, 0.34.

in meteorites by neutron activation. For 32 olivine-bronzite chondrites they find an average of 17.0 per cent of Si, equivalent to 36.4 per cent of SiO_2, in close correspondence to the figure from the chemical analyses. For 59 olivine-hypersthene chondrites their average is 18.1 per cent of Si, equivalent to 38.8 per cent of SiO_2, about 1 per cent less than the figure from the chemical analysis. The figures from the chemical analyses are preferred.

MgO: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 21.99 per cent (analysis 2) to 24.82 per cent (analyses 167, 194), and the mean is 23.53 per cent (fig. 3). For the olivine-hypersthene chondrites the range is from 23.31 per cent (analysis 147) to 26.49 per cent (analysis 179), and the mean is 25.16 per cent (fig. 4).

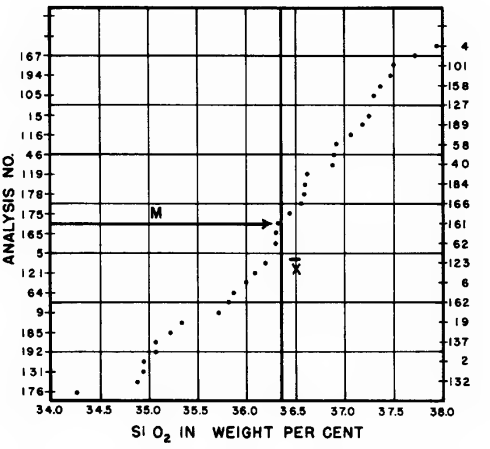

FIG. 1. SiO_2 in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

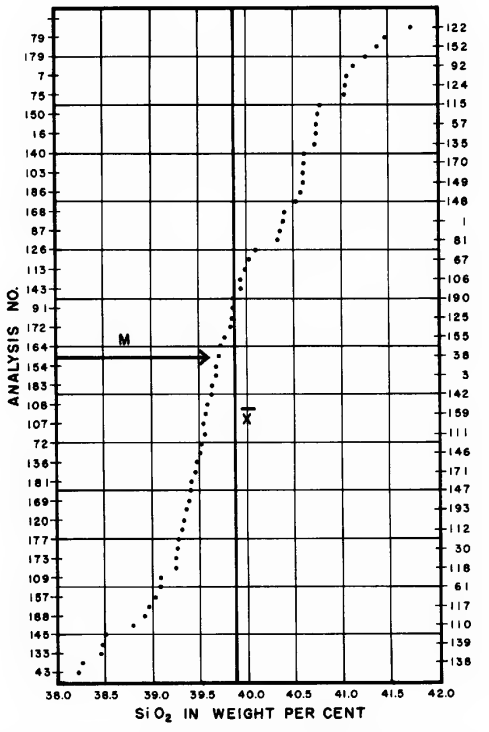

FIG. 2. SiO_2 in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

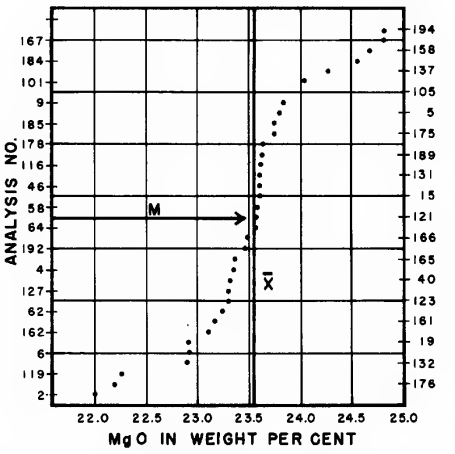

FIG. 3. MgO in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

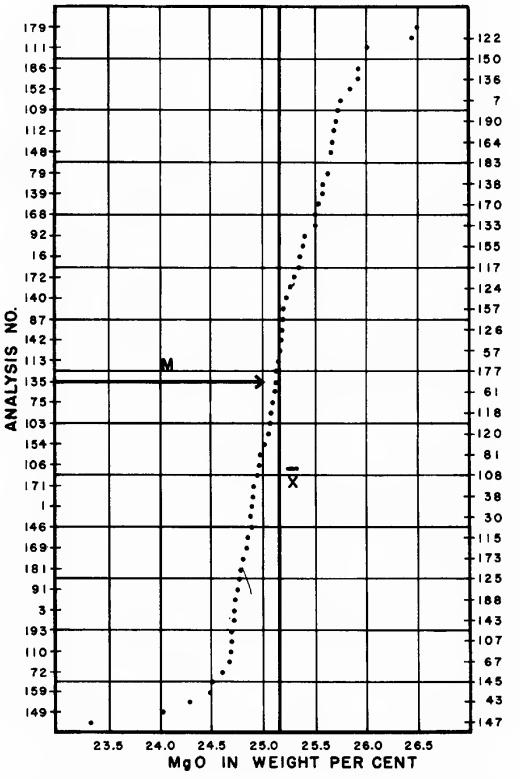

FIG. 4. MgO in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

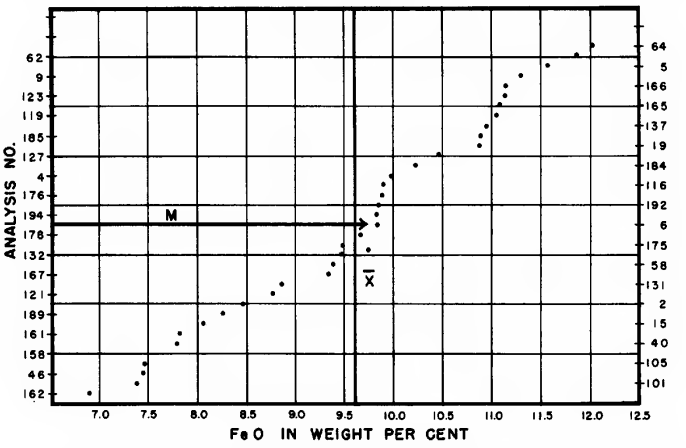

FIG. 5. FeO in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

FeO: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 6.90 per cent (analysis 162) to 12.01 per cent (analysis 64), with a mean of 9.61 per cent (fig. 5). For the olivine-hypersthene chondrites the range is from 11.57 per cent (analysis 152) to 21.11 per cent (analysis 103), with a mean of 14.66 per cent (fig. 6). The latter mean is considerably greater than the 13.12 per cent given by Craig (1964), owing to my having included with the olivine-hypersthene chondrites the so-called soko-banjites, which all have rather high FeO; the validity of a separate group of soko-banjites is discussed below.

Al_2O_3: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 1.50 per cent (analysis 40) to 4.82 per cent (analysis 158), and the mean is 2.66 per cent (fig. 7). For the olivine-hypersthene chondrites the range is from 1.26 per cent (analysis 152) to 4.35 per cent (analysis 149), and the mean is 2.51 per cent (fig. 8). These means are certainly too high, which is caused by the down-rating of analyses with too low Al_2O_3 ($Al_2O_3 < Na_2O + K_2O$), while analyses in which the Al_2O_3 is probably considerably higher than the true figure are retained. Fisher (1964) has measured aluminum in chondrites by neutron activation. The average for four olivine-bronzite chondrites is 1.29 per cent, equivalent to 2.43 per cent of Al_2O_3, and for six olivine-hypersthene chondrites 1.35 per cent, equivalent to 2.54 per cent of Al_2O_3. Craig's (1964) means are 2.43 per cent and 2.31 per cent of Al_2O_3, respectively. Most of the aluminum in a chondrite is present as plagioclase feldspar (oligoclase), usually about 9 per cent, which would require about 2.0 per cent of Al_2O_3; a little aluminum is also combined in pyroxene. The true

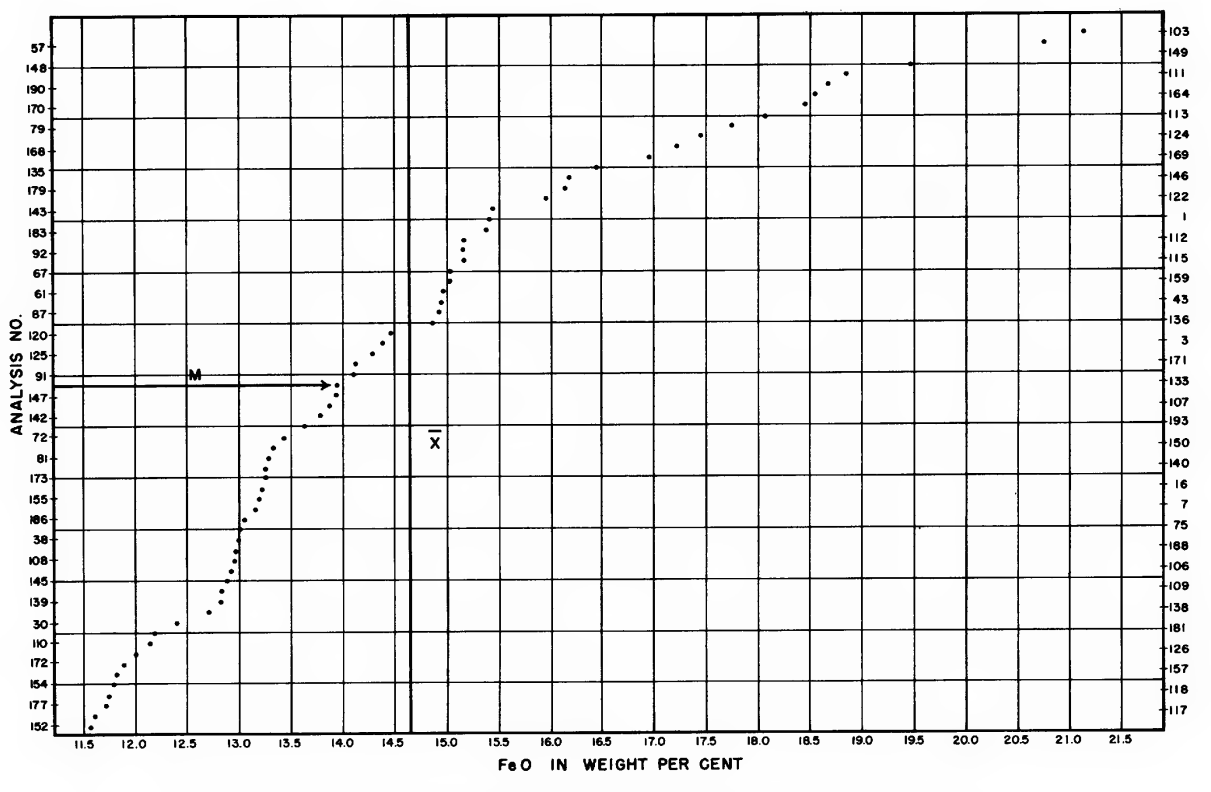

FIG. 6. FeO in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

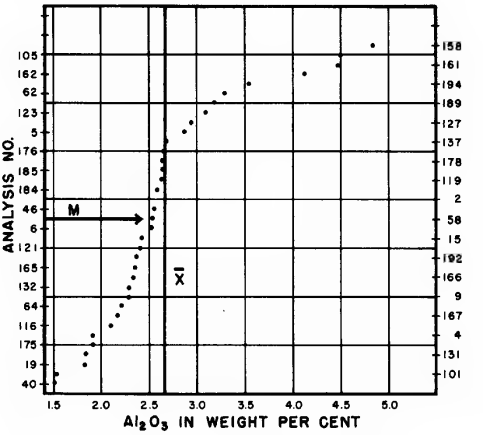

FIG. 7. Al_2O_3 in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

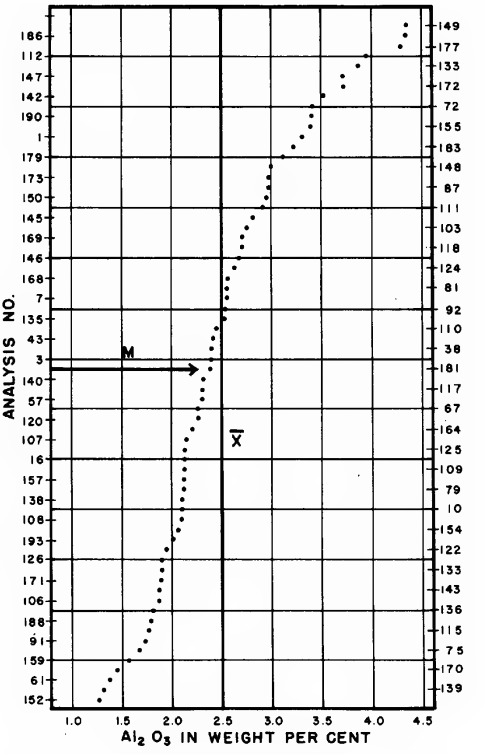

FIG. 8. Al_2O_3 in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

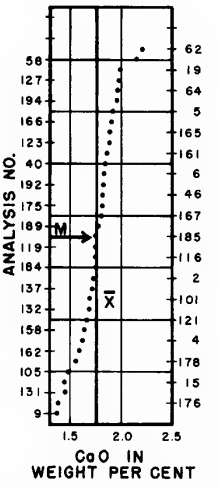

FIG. 9. CaO in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

mean is probably approximately 2.3 per cent to 2.4 per cent.

Since the sodium and virtually all the aluminum in common chondrites is combined as plagioclase of rather uniform composition, the

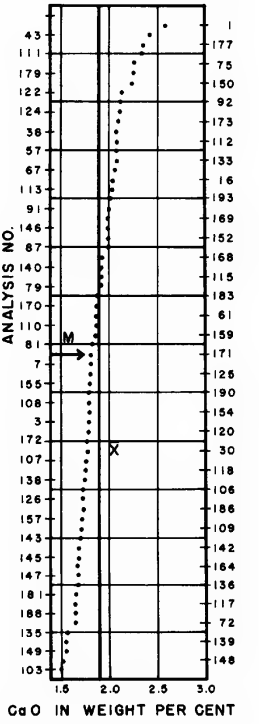

FIG. 10. CaO in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

amounts of Na_2O and Al_2O_3 in different analyses should show a direct relationship. In view of the uniformity of mineralogical composition of the common chondrites, it appears that the range of Al_2O_3 is not greater than 1.8 per cent to 2.8 per cent and is probably less; analytical results outside this range are suspect, unless explicable on the basis of sampling or mineralogy.

CaO: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 1.38 per cent (analysis 9) to 2.21 per cent (analysis 62), and the mean is 1.76 per cent (fig. 9). For the olivine-hypersthene chondrites the range is from 1.50 per cent (analysis 103) to 2.60 per cent (analysis 1), and the mean is 1.89 per cent (fig. 10). These means are in good agreement with those of Craig (1964), and appear to be an accurate representation of the calcium content in the common chondrites. It is therefore intriguing to find that it is difficult to account for this amount of calcium in the minerals of the common chondrites. Calcium is combined with P_2O_5 as whitlockite or apatite, or both, both of which are phosphates, as plagioclase (normally oligoclase, composition around An_{10}), and as orthopyroxene (average 0.5 per cent of Ca, according to Keil and Fredriksson, 1964). With the average content of these minerals, we can account for CaO as follows:

	CaO, %
30% orthopyroxene	0.2
9% oligoclase	0.3
1% phosphate	0.4
	0.9

We have thus accounted for 0.9 per cent of CaO, or half of that shown by chemical analysis. Some of the remainder may be present as diopside, but this seems to be a trace constituent. Diopside has a CaO content of about 20 per cent, and 1 per cent of this mineral would account for 0.2 per cent of CaO. Recent investigations (Mason, unpublished) have shown that many chondrites contain not only orthopyroxene but also considerable amounts of clinopyroxene (clinobronzite or clinohypersthene). This phase is always fine-grained and very difficult to distinguish with the microscope, and its diffraction pattern overlaps that of orthopyroxene, and on that account it has been often overlooked. The clinobronzite or clinohypersthene probably contains considerably more calcium than orthopyroxene, thereby accounting for the over-all CaO content of these meteorites.

Na_2O: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.55 per cent (analysis 161) to 1.26 per cent (analysis 194), and the mean is 0.86 per cent (fig. 11). In the olivine-

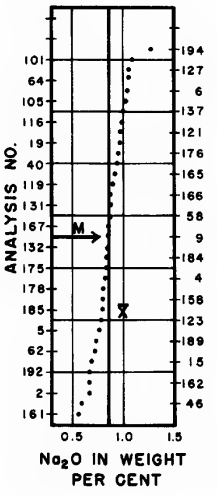

FIG. 11. Na_2O in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

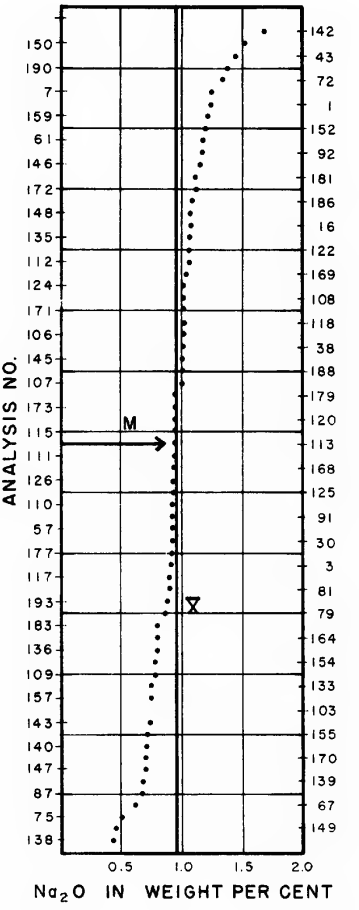

FIG. 12. Na_2O in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

hypersthene chondrites the range is from 0.43 per cent (analysis 138) to 1.67 per cent (analysis 142), and the mean is 0.95 per cent (fig. 12). An independent check on these figures is provided by the work of Edwards (1955), who determined sodium in chondrites by a distillation method. He found a remarkably uniform content, the mean for 12 olivine-bronzite falls being 0.66 per cent of Na, equivalent to 0.89 per cent of Na_2O, and for 25 olivine-hypersthene falls 0.70 per cent of Na, equivalent to 0.94 per cent of Na_2O. His work indicates that the range in sodium content is much less than that shown by the chemical analyses, probably not more than 0.8–1.0 per cent of Na_2O. This is supported by the relative constancy in the amount of plagioclase in the common chondrites.

K_2O: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.05 per cent (analysis 6) to 0.23 per cent (analysis 2), with a mean of 0.12 per cent. In the olivine-hypersthene chondrites the range is from 0.04 per cent (analysis 3) to 0.38 per cent (analysis 43), with a mean of 0.15 per cent. The relative constancy in Na_2O indicates that K_2O should also be relatively constant, and the above ranges probably reflect the difficulty in the accurate determination of small amounts of potassium by classical analytical procedures. Fortunately, an independent check is provided by the numerous potassium determinations by instrumental methods, made in recent years for potassium-argon dating. Kirsten, Krankowsky, and Zähringer (1963) have collected these data, and the figures show that the potassium content of the common chondrites ranges from about 0.07 per cent to 0.10 per cent, equivalent to 0.09 per cent to 0.12 per cent of K_2O. Evidently the above means are not very far from the true values, but are probably a little high.

Cr_2O_3: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.10 per cent (analysis 10) to 0.68 per cent (analysis 158), with one highly exceptional value of 1.18 per cent (analysis 131); the mean is 0.42 per cent. In the olivine-hypersthene chondrites the range is from 0.07 per cent (analysis 112) to 0.87 per cent (analysis 188), with a mean of 0.45 per cent. If this were all combined as chromite, one should find almost 1 per cent of this mineral in the common chondrites. Such is not the case; chromite is much less abundant, usually amounting to about 0.2 per cent to 0.3 per cent (Keil, 1962). Evidently the major part of the chromium is combined in pyroxene; Miyashiro (1962) records 0.8 per cent of Cr_2O_3 in an analysis of orthopyroxene from the Kesen chondrite.

MnO: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.04 per cent (analysis 15) to 0.40 per cent (analysis 189), with a mean of 0.25 per cent. For the olivine-hyper-

sthene chondrites the range is from 0.05 per cent (analysis 79) to 0.50 per cent (analysis 190), with a mean of 0.29 per cent. Moore and Brown (1962) made a large number of spectrographic determinations of manganese. For 17 olivine-bronzite falls the mean is 0.253 per cent of Mn, equivalent to 0.33 per cent of MnO; for 20 olivine-hypersthene falls the mean is 0.270 per cent of Mn, equivalent to 0.35 per cent of MnO. The difference between the chemical determinations and the spectrographic ones is not great, although the spectrographic determinations are consistently a little higher.

The distribution of manganese in the minerals of the common chondrites has not been studied; it is presumably present largely or entirely in the olivine and pyroxene.

TiO_2: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.07 per cent (analyses 4, 192) to 0.34 per cent (analysis 158), with a mean of 0.15 per cent. For the olivine-hypersthene chondrites the range is from 0.02 per cent (analysis 72) to 0.42 per cent (analysis 190), with a mean of 0.15 per cent. This range is not consistent with the constancy of mineralogical composition of the common chondrites, and Moore and Brown (1962), by spectrographic analysis of a large number of chondrites, found a rather constant titanium content. For 17 olivine-bronzite falls the mean was 0.062 per cent of Ti, equivalent to 0.103 per cent of TiO_2; for 20 olivine-hypersthene falls the mean was 0.066 per cent of Ti, equivalent to 0.110 per cent of TiO_2. The chemically determined means are somewhat higher than those found by spectrographic analysis.

P_2O_5: Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.00 per cent (analysis 123) to 0.53 per cent (analysis 176), with a mean of 0.26 per cent. For the olivine-hypersthene chondrites the range is from 0.00 per cent (analyses 138, 139) to 0.68 per cent (analysis 75), with a mean of 0.27 per cent. The above ranges are probably much greater than the true ranges, but an independent check is not available. In the common chondrites phosphorus is present as chlorapatite or whitlockite (merrillite) or both; small inclusions of schreibersite have been observed in the metal phase, but these probably account for only a little of the total phosphorus.

Fe: Individual determinations in the selected analyses of the olivine-bronzite chondrites range from 13.54 per cent (analysis 194) to 21.09 per cent (analysis 2), with a mean of 16.79 per cent (fig. 13). For the olivine-hypersthene chondrites the range is from 0.33 per cent (analysis 103) to 9.83 per cent (analysis 117), with a mean of 6.28 per cent (fig. 14). These ranges are much greater than those for most components, but, as pointed

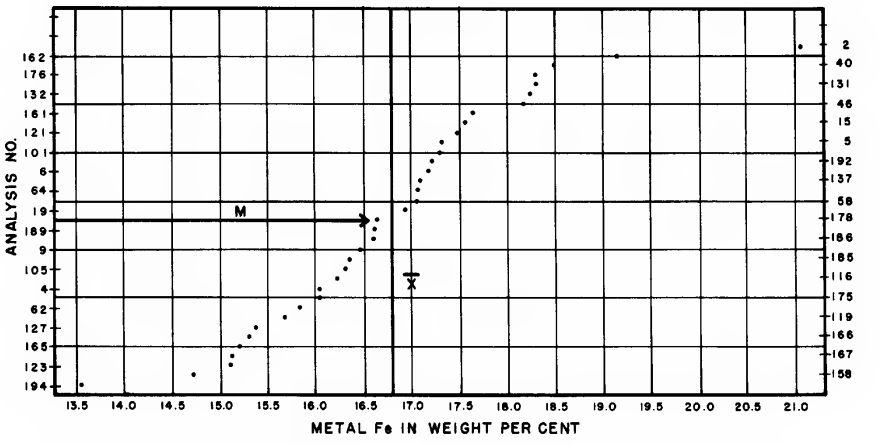

FIG. 13. Metal Fe in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

out previously, Fe and FeO show an inverse relationship.

NI: Individual determinations in the selected analyses of the olivine-bronzite chondrites range from 1.21 per cent (analysis 62) to 1.93 per cent (analyses 64, 101), with a mean of 1.63 per cent (fig. 15). For the olivine-hypersthene chondrites the range is from 0.39 per cent (analysis 170) to 1.48 per cent (analysis 139), with a mean of 1.10 per cent (fig. 16).

Co: Cobalt is frequently considered as a trace constituent and not determined in the usual chemical analysis. Individual determinations in the selected analyses of olivine-bronzite chondrites range from 0.02 per cent (analyses 58, 62) to 0.23 per cent (analysis 15), with a mean of 0.089 per cent. For the olivine-hypersthene chondrites the range is from 0.02 per cent (analyses 57, 87, 92, 117, 118, 170) to 0.14 per cent (analysis 67), with a mean of 0.059 per cent.

METAL: The figure for this phase is determined by the addition of Fe, Ni, Co, and is largely controlled by the amount of Fe. For the olivine-bronzite analyses the range is from 15.03 per cent (analysis 194) to 23.05 per cent (analysis 1; this figure is exceptionally high, the nearest being the 20.82 per cent of analysis 162), and the mean is 18.48 per cent. For the olivine-hypersthene chondrites the range is from 1.20 per cent (analysis 57) to 11.18 per cent (analysis 117), and the mean is 7.41 per cent. These figures may be compared with the direct measurements of metal content by Keil (1962). He found the range in the olivine-bronzite chondrites (falls only) to be from 14.42 per cent (Heredia) to 19.81 per cent (Seres), and the mean 17.18 per cent, and the range in the olivine-

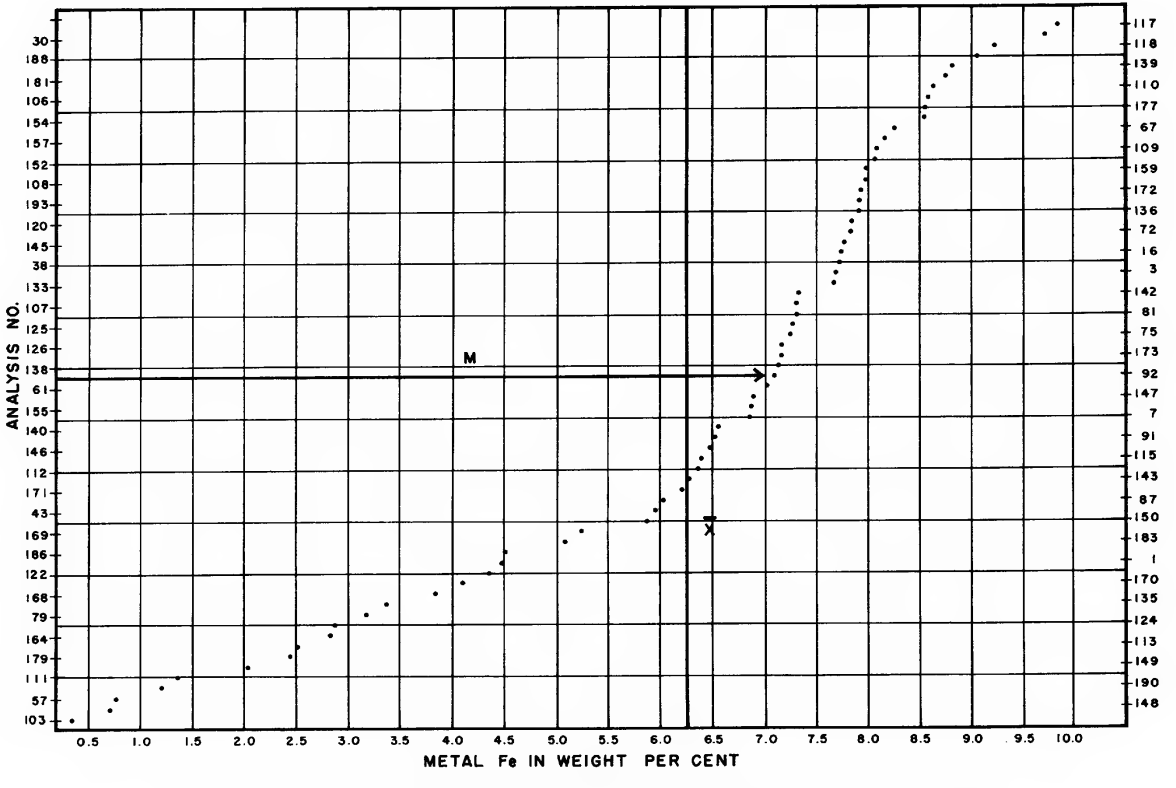

FIG. 14. Metal Fe in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

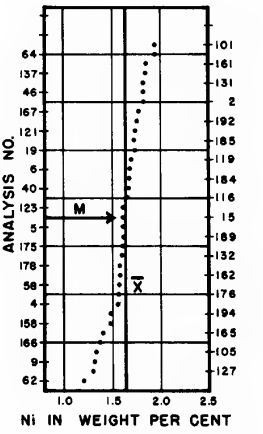

FIG. 15. Ni in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

hypersthene chondrites to be from 1.56 per cent (Ergheo) to 11.65 per cent (L'Aigle), with a mean of 6.59 per cent.

FeS: This figure is calculated from the total sulphur determined in the chemical analysis. The assumption that all sulphur in the common

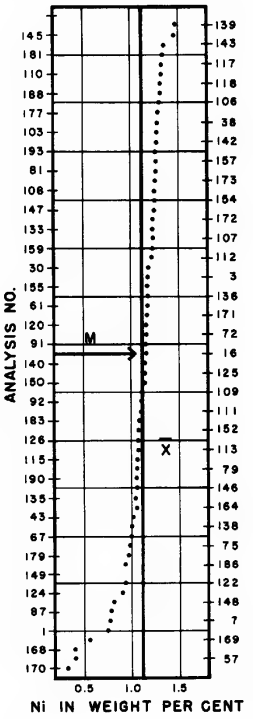

FIG. 16. Ni in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

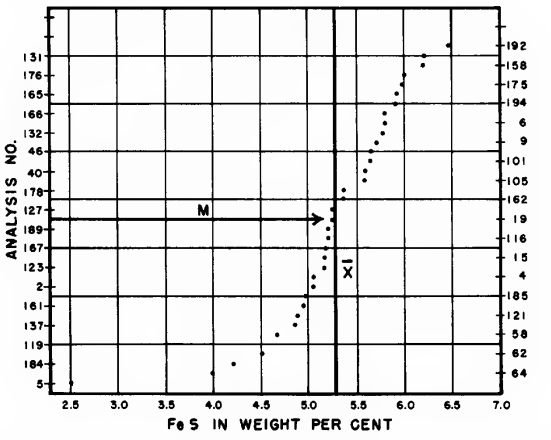

FIG. 17. FeS in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

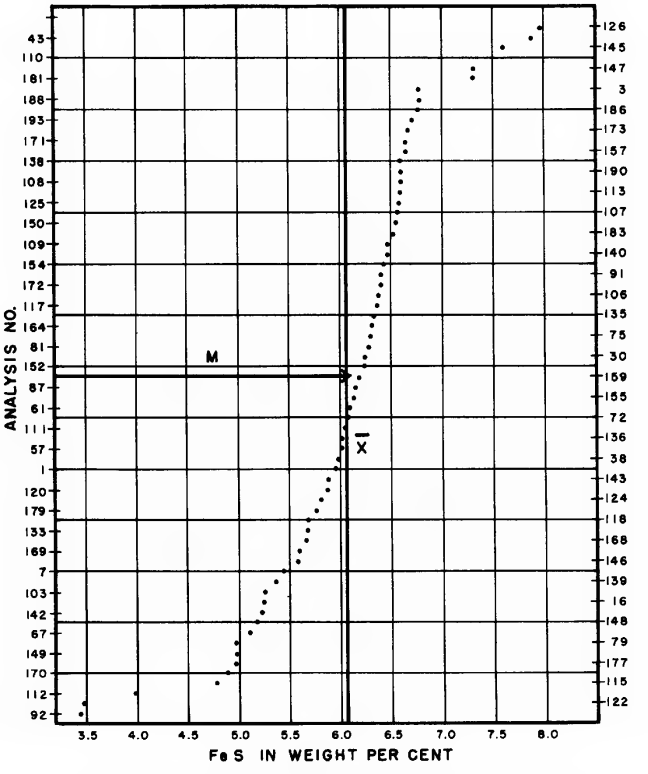

FIG. 18. FeS in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

chondrites is present as FeS is essentially correct, although trace amounts of other sulphide minerals have been recorded in some of these meteorites (Ramdohr, 1963). For the olivine-bronzite chondrites the range is from 2.52 per cent (analysis 5) to 6.47 per cent (analysis 192), and the mean is 5.27 per cent, equivalent to 1.92 per cent of S (fig. 17). For the olivine-hypersthene chondrites the range is from 3.46 per cent (analysis 92) to 7.94 per cent (analysis 126), and the mean is 6.07 per cent, equivalent to 2.21 per cent of S (fig. 18). It is interesting to note that in the original

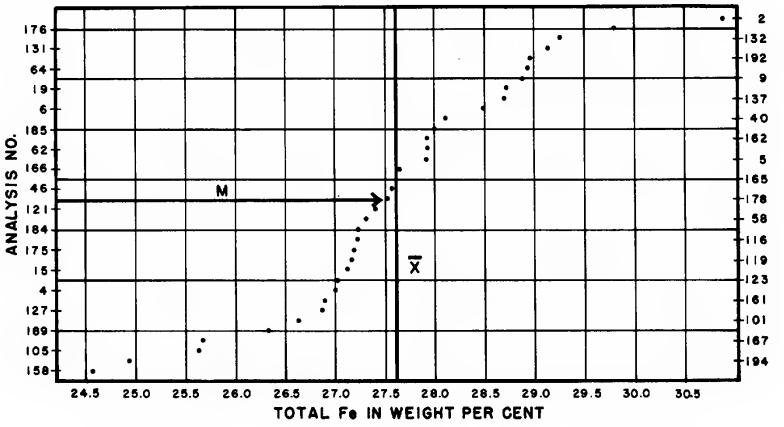

FIG. 19. Total Fe in olivine-bronzite chondrites; M, median; $\bar{x}$, mean.

computations of Urey and Craig (1953) the amount of FeS in the two groups was essentially identical, whereas the present computations and those of Craig (1964) show clearly that the olivine-hypersthene chondrites are richer in FeS than the olivine-bronzite chondrites. The chemically determined FeS is somewhat higher than the figures for the troilite content of chondrites given by Keil (1962); he found an average of 5.03 per cent of troilite in olivine-bronzite chondrites and 5.54 per cent of troilite in olivine-hypersthene chondrites. The discrepancy can probably be explained by the difficulty of recording all the minute grains of troilite in micrometric analysis.

TOTAL FE: Whereas Fe and FeO are quite variable in the two groups of the common chondrites, total Fe in each of these groups is rather constant, as first established by Urey and Craig (1953). For the selected analyses of olivine-bronzite chondrites the range is from 24.57 per cent (analysis 158) to 30.88 per cent (analysis 2), with a mean of 27.61 per cent (fig. 19). For the olivine-hypersthene chondrites the range is from

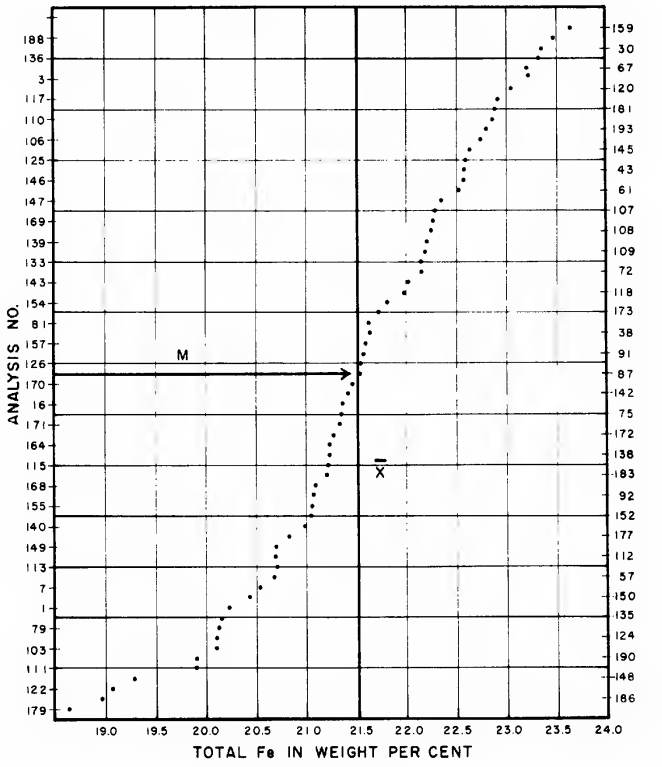

FIG. 20. Total Fe in olivine-hypersthene chondrites; M, median; $\bar{x}$, mean.

18.64 per cent (analysis 179) to 23.61 per cent (analysis 159), with a mean of 21.53 per cent (fig. 20).

Table 4 gives "preferred" average compositions for the olivine-bronzite and olivine-hypersthene chondrites, calculated to 100.00 from the means of table 3, with modifications for Al_2O_3, K_2O, MnO, and TiO_2. The modifications for K_2O, MnO, and TiO_2 are quite minor; for K_2O the slightly lower figures indicated by recent instrumental analyses are adopted, and for MnO and TiO_2 the spectrographic data of Moore and Brown are used. For Al_2O_3 the figures of 2.30 per cent and 2.40 per cent for the olivine-bronzite and olivine-hypersthene chondrites, respectively, are adopted. It was pointed out that the means of the chemical analyses are somewhat higher than the true values, because of the inclusion of some high values which are certainly erroneous; also the figures for all the oxide components in the olivine-hypersthene chondrites are higher than in the olivine-bronzite chondrites, and this relationship presumably

TABLE 4

PREFERRED VALUES FOR THE AVERAGE COMPOSITION OF OLIVINE-BRONZITE AND OLIVINE-HYPERSTHENE CHONDRITES

	1	2		3	4	5	6
SiO_2	36.57	39.98	O	33.24	36.91	34,130	34,670
MgO	23.69	25.23	Fe	27.79	21.60	8,175	5,815
FeO	9.67	14.70	Si	17.10	18.69	10,000	10,000
Al_2O_3	2.30	2.40	Mg	14.29	15.22	9,651	9,406
CaO	1.77	1.90	S	1.93	2.22	989	1,041
Na_2O	0.86	0.95	Ni	1.64	1.10	459	282
Cr_2O_3	0.42	0.45	Ca	1.27	1.36	521	510
MnO	0.33	0.35	Al	1.22	1.27	743	708
P_2O_5	0.26	0.27	Na	0.64	0.71	457	464
K_2O	0.10	0.11	Cr	0.29	0.31	92	90
TiO_2	0.10	0.11	Mn	0.25	0.27	78	74
Fe	16.90	6.30	P	0.11	0.12	58	58
Ni	1.64	1.10	Co	0.09	0.06	25	15
Co	0.09	0.06	K	0.08	0.09	34	35
FeS	5.30	6.09	Ti	0.06	0.07	21	22
	100.00	100.00		100.00	100.00		

1 Average composition (per cent by weight) of olivine-bronzite chondrites
2 Average composition (per cent by weight) of olivine-hypersthene chondrites
3 Average elemental composition (per cent by weight) of olivine-bronzite chondrites
4 Average elemental composition (per cent by weight) of olivine-hypersthene chondrites
5 Atoms per 10,000 Si for average of olivine-bronzite chondrites
6 Atoms per 10,000 Si for average of olivine-hypersthene chondrites

holds for Al_2O_3 also, as is indicated by the neutron activation analyses of Fisher.

MINERALOGICAL COMPOSITION OF THE OLIVINE-BRONZITE AND OLIVINE-HYPERSTHENE CHONDRITES

The norm calculated from the chemical analysis of a common chondrite usually corresponds rather closely to the actual mineralogical composition, or mode, because the normative "minerals" are essentially the same as the actual minerals, since hydrated minerals such as amphibole and mica which introduce complications in terrestrial rocks are absent from meteorites. Table 5 gives the norms calculated from the average compositions of the olivine-bronzite and the olivine-hypersthene chondrites. Possible discrepancies between the norm and the mode include: (1) lower chromite in the mode, because much of the chromium is combined in pyroxene; (2) little or no ilmenite in the mode, much of the titanium being in pyroxene; (3) actual plagioclase somewhat more sodic

than normative plagioclase, some of the Ca, Al, and Si calculated as anorthite being in the pyroxene. None of these discrepancies have a very large affect, the principal result being that modal pyroxene will be somewhat higher (1%–2%) than normative pyroxene.

The actual amounts and proportions of pyroxene and olivine in a specific chondrite are controlled by the amount of FeO available, which varies within each of the two groups. For the olivine-bronzite chondrites FeO varies from about 7 per cent to 12 per cent, and for the olivine-

TABLE 5

NORMATIVE MINERALOGICAL COMPOSITION CALCULATED FROM THE AVERAGE CHEMICAL ANALYSES OF THE OLIVINE-BRONZITE CHONDRITES (1) AND THE OLIVINE-HYPERSTHENE CHONDRITES (2)

	1	2
Olivine	36.2	47.0
Orthopyroxene	24.5	22.7
Diopside	4.0	4.6
Orthoclase	0.6	0.6
Albite	7.3	8.1
Anorthite	2.1	2.0
Apatite	0.6	0.6
Chromite	0.6	0.6
Ilmenite	0.2	0.2
Troilite	5.3	6.1
Nickel-iron	18.6	7.5
	100.0	100.0

hypersthene chondrites it varies from about 12 per cent to 21 per cent. Within each group, the greater the amount of FeO the greater the amount of olivine relative to pyroxene. In the olivine-bronzite chondrites the amount of olivine varies from about 30 per cent to 40 per cent, and in the olivine-hypersthene chondrites from about 40 per cent to 53 per cent.

RELATIONSHIP BETWEEN FeO AND Fe WITHIN OLIVINE-BRONZITE AND OLIVINE-HYPERSTHENE CHONDRITE GROUPS

Ringwood (1961) and Mason (1962) have published diagrams showing the relationship between oxidized and reduced iron in the chondrites, using data from chemical analyses which had been checked by physical measurements of the composition of the olivine. Craig (1964, p. 416) stated that the ranges in composition shown by these diagrams are spuri-

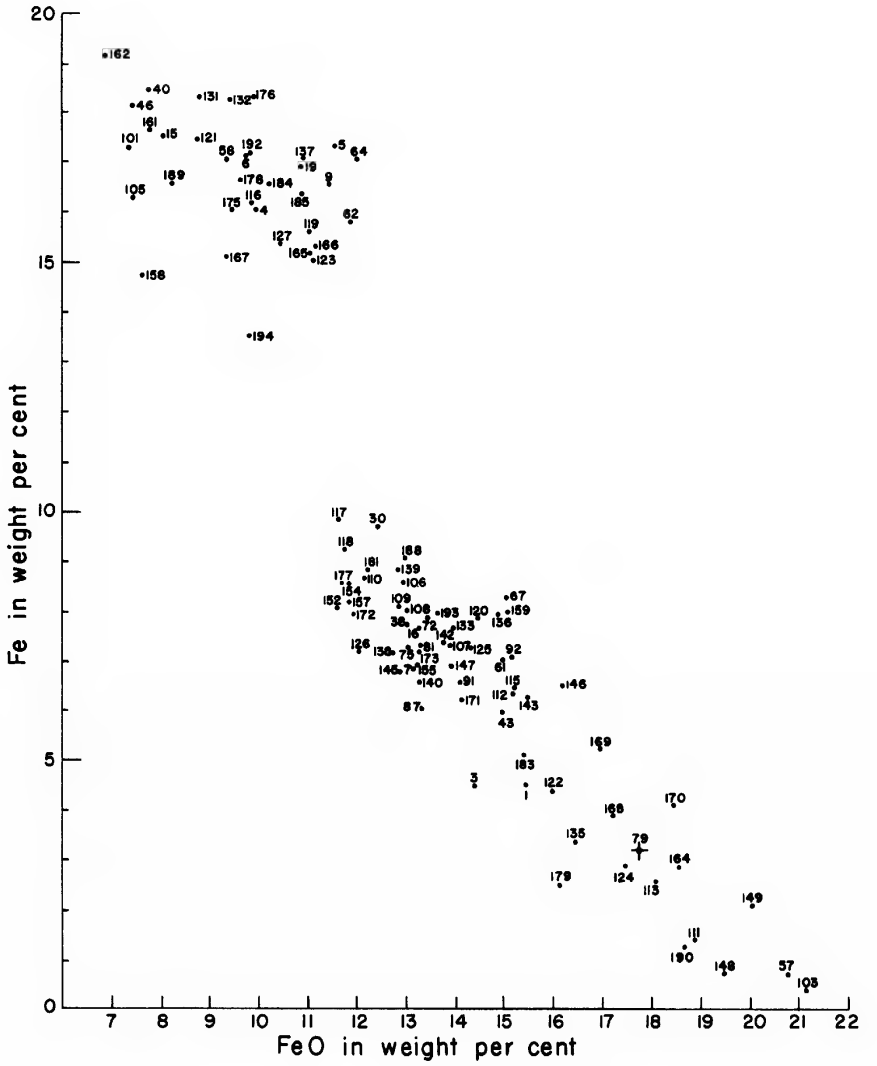

FIG. 21. The relationship between Fe (metal) and FeO in the olivine-bronzite (13%–20% Fe) and olivine-hypersthene chondrites (0%–10% Fe). No. 79 is Soko-Banja.

ous, owing to analytical errors and terrestrial oxidation. He prefers to take the range in composition as that established by Keil and Fredriksson (1964), determined by measurements on 86 chondrites, or less than 10 per cent of the total known.

Craig's statement that the range of composition established by Ringwood and Mason is spurious owing to the terrestrial oxidation of the meteorites completely overlooks the fact that Mason's diagram expressly excluded finds because of the possibility of such oxidation, and Ringwood's diagram included only two finds, Elsinora and McKinney. His claim that the range in composition is due to analytical error ignores the clear statement (Mason, 1962) that the diagram used analyses of observed falls that had been checked against the composition of the minerals. Further work (Mason, 1963) has amply confirmed a considerable range of composition in the olivine of the common chondrites. In 364 olivine-bronzite chondrites the olivine composition ranges from Fa_{14} to Fa_{21}; in 427 olivine-hypersthene chondrites the olivine composition ranges from Fa_{22} to Fa_{31}. For the olivine-bronzite chondrites this corresponds to a range in FeO content from about 7 per cent to 12 per cent; for the olivine-hypersthene chondrites a range in FeO content from about 12 per cent to 21 per cent. The Fe and FeO contents of the selected analyses from tables 1 and 2 plotted on figure 21 show this range quite clearly.

Suess (1964) also used the data of Keil and Fredriksson on olivine and pyroxene compositions in the common chondrites as the basis of his statement (p. 385), "No correlation between the FeO content of the silicates and the metal content of the respective meteorite is apparent." On the contrary, figure 21 shows that this correlation is quite good, being especially well marked in the olivine-hypersthene chondrites, in which compositional range is somewhat greater than in the olivine-bronzite chondrites.

VALIDITY OF A SOKO-BANJITE GROUP

Prior, in his initial classification (1916), divided the chondrites into groups, the groups being named for a specific meteorite. In 1920 he revised this classification and named the groups according to their mineralogy. The two classifications can be summarized thus:

1916	1920
Daniel's Kuil group	Enstatite chondrites
Cronstad group	Olivine-bronzite chondrites
Baroti group, Soko-Banja group	Olivine-hypersthene chondrites

i.e., in 1920 he considered Baroti and Soko-Banja to belong to a single group, the olivine-hypersthene chondrites.

Craig (1964) has proposed that Soko-Banja and meteorites of similar composition (he listed Soko-Banja, Douar Mghila, Isoulane, Olivenza,

Ottawa, Oubari, Vavilovka, Chicora, Dhurmsala, Jelica, Manbhoom, and Mangwendi) be separated as a distinct group known as soko-banjites. He wrote: "The soko-banjites form a distinct group on a reduced iron vs. oxidized iron diagram of chondrites, with a little less total iron than the Low Iron chondrites and a much higher state of oxidation."

Keil and Fredriksson (1964) have also proposed that Soko-Banja and meteorites of similar composition be included in a distinct group of chondrites. They call this group the LL group, distinct from the H and L groups of Urey and Craig. They wrote: ". . . the total iron content in the Soko-Banja group is almost the same as in the L group chondrites, whereas the metallic nickel-iron content is considerably lower. For this reason the group constituted of Soko-Banja chondrites should properly be designated the low iron-low metal (or LL group) of chondrites." Of the 86 chondrites they examined, five (Dhurmsala, Cherokee Springs, Oberlin, Soko-Banja, and Vårvik, also known as Näs) were classified in their LL group. The low metallic nickel-iron content of the LL group is a consequence of the large amount of ferrous iron combined in the silicates.

Some of Craig's soko-banjites are meteorites that have long been known as amphoterites (Manbhoom, Jelica, Vavilovka). The amphoterites have been considered a class of achondrites, but Kvasha (1958) showed that Manbhoom, Jelica, and Vavilovka all contain chondrules, and concluded that the amphoterites did not constitute a specific class of meteorites, but were to be regarded as brecciated chondrites. Mason and Wiik (1964) discussed the amphoterites and meteorites of similar composition and concluded they . . . "comprise a subclass of rather uniform and distinctive chemical and mineralogical composition within the olivine-hypersthene chondrites."

We thus have three names (soko-banjites, LL group, and amphoterites) for a number of meteorites which certainly differ little in elemental composition from the olivine-hypersthene chondrites. The distinguishing feature of the soko-banjites is their higher content of FeO and lower content of Fe. Craig, and Keil and Fredriksson, evidently believe a compositional hiatus exists between their L-group chondrites and the soko-banjites. However, such does not seem to be the case, when one surveys a large number of these meteorites. In figure 21 the FeO and Fe contents of all the meteorites included in the selected analyses of the olivine-hypersthene chondrites are plotted. The variation is continuous, and no hiatus can be seen. Any compositional boundary between the soko-banjites and the other olivine-hypersthene chondrites must be an arbitrary one. The utility, therefore, of creating a separate group for Soko-Banja and meteorites of similar composition is not obvious.

TABLE 6

POSSIBLE DERIVATION OF OLIVINE-HYPERSTHENE CHONDRITE MATERIAL FROM OLIVINE-BRONZITE MATERIAL

	1	2	3	4
Fe	27.79	19.62	21.56	21.60
Ni	1.64	0.85	0.93	1.10
Co	0.09	0.05	0.06	0.06
Si	17.10	17.10	18.79	18.69
Mg	14.29	14.29	15.70	15.22
Al	1.22	1.22	1.34	1.27
Ca	1.27	1.27	1.40	1.36
Na	0.64	0.64	0.70	0.71
K	0.08	0.08	0.09	0.09
Cr	0.29	0.29	0.32	0.31
Mn	0.25	0.25	0.27	0.27
Ti	0.06	0.06	0.07	0.07
P	0.11	0.11	0.12	0.12
S	1.93	1.93	2.12	2.22
O	33.24	33.24	36.53	36.91
	100.00	91.00	100.00	100.00

1 Average elemental composition (per cent by weight) of olivine-bronzite chondrites
2 Column 1, minus 9 per cent of nickel-iron
3 Column 2, recalculated to 100.00
4 Average elemental composition (per cent by weight) of olivine-hypersthene chondrites

RELATIONSHIP BETWEEN THE OLIVINE-BRONZITE (H-GROUP) CHONDRITES AND OLIVINE-HYPERSTHENE (L-GROUP) CHONDRITES

Urey and Craig (1953, p. 60) made the statement, "it is not possible to go from one group to the other by the addition or subtraction of metal phase." In spite of this categorical assertion, it may be worthwhile to re-evaluate this statement in the light of the revised data now available. Table 6 shows the results of recalculating the average composition of the olivine-bronzite chondrites after the removal of 9 per cent of the metal phase. The composition thus arrived at shows a close correspondence with the average composition of the olivine-hypersthene chondrites. It would indeed be remarkable if the results for 15 independently determined components coincided so well as a result of pure chance. One would hesitate to claim that this proves the material of the olivine-hypersthene chondrites was derived from that of the olivine-bronzite chondrites by the simple abstraction of 9 per cent of nickel-iron; natural processes may well be far more complicated than we can conceive. Never-

theless, the relationship is apparent and merits careful consideration.

If we accept the proposal that the material of the olivine-hypersthene chondrites was derived from that of the olivine-bronzite chondrites by the removal of 9 per cent of nickel-iron, the question arises: "How was the metal removed, and where did it go?" Again, the simplest explanation is that it was removed by fractional melting, the nickel-iron being more readily fusible than the silicate phases. Where did it go? Possibly we have here the source of the iron meteorites. Lovering (1957) has shown that the relative weights and abundances of the iron meteorites of different types can be derived by the fractional crystallization of an initial nickel-iron melt containing about 11 per cent of nickel. Such a melt could be provided by the fractional melting process suggested above.

An alternative possibility is that these two groups of chondrites formed independently from parent material differing somewhat in total iron (and nickel and cobalt) content. If the chondrites aggregated directly from a pre-planetary dust cloud, they may represent material from different regions within this dust cloud. Possibly in such a dust cloud magnetic influences could have caused a relative concentration of free nickel-iron particles in the region from which the olivine-bronzite chondrites have been derived, and a relative diminution of free nickel-iron in the region of formation of the olivine-hypersthene chondrites. A partial fractionation of nickel-iron in this way would thus result in the primary formation of these two groups of chondrites with their characteristic differences in chemical composition.

CONCLUSIONS

1. The olivine-bronzite and olivine-hypersthene chondrites, comprising more than 90 per cent of all chondrites, form two distinct groups of meteorites of remarkably uniform chemical composition.

2. Within each group, compositional differences are essentially the inverse relationship of free Fe and FeO, over a clearly defined range.

3. The average composition of the olivine-hypersthene chondrites can be derived from that of the olivine-bronzite chondrites by the removal of 9 per cent of the metal phase from the latter.

4. The meteorites known variously as amphoterites, soko-banjites, LL-group, are olivine-hypersthene chondrites high in FeO and low in free Fe, but continuous in composition with the other meteorites in this group.

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REFERENCES

CRAIG, H.
1964. Petrological and compositional relationships in meteorites. *Chapter 26 in* Craig, H., S. L. Miller, and G. J. Wasserburg (eds.), Isotopic and cosmic chemistry. Amsterdam, North-Holland Publishing Co., pp. 405–451.

EDWARDS, G.
1955. Sodium and potassium in meteorites. Geochim. et Cosmochim. Acta, vol. 8, pp. 285–294.

FISHER, D. E.
1964. The aluminum content of chondritic meteorites as determined by activation analysis. Geochim. et Cosmochim. Acta, vol. 28, pp. 743–750.

KEIL, K.
1962. Quantitativ-erzmikroskopische Integrationsanalyse der Chondrite. Chem. Erde, vol. 22, pp. 281–348.

KEIL, K., AND K. FREDRIKSSON
1964. The iron, magnesium, and calcium distribution in coexisting olivines and rhombic pyroxenes of meteorites. Jour. Geophys. Res., vol. 69, pp. 3487–3517.

KIRSTEN, T., D. KRANKOWSKY, AND J. ZÄHRINGER
1963. Edelgas und Kalium-Bestimmungen an einer grösseren Zahl von Steinmeteoriten. Geochim. et Cosmochim. Acta, vol. 27, pp. 13–42.

KVASHA, L. G.
1958. Über einige Typen von Steinmeteoriten. Chem. Erde, vol. 19, pp. 249–274.

LOVERING, J. F.
1957. Differentiation in the iron-nickel core of a parent meteorite body. Geochim. et Cosmochim. Acta, vol. 12, pp. 238–252.

MASON, B.
1962. Meteorites. New York, John Wiley and Sons, 274 pp.
1963. Olivine composition in chondrites. Geochim. et Cosmochim. Acta, vol. 27, pp. 1011–1023.

MASON, B., AND H. B. WIIK
1964. The amphoterites and meteorites of similar composition. Geochim. et Cosmochim. Acta, vol. 28, pp. 533–538.

MIYASHIRO, A.
1962. The Kesen, Japan, chondrite. Japanese Jour. Geol. Geogr., vol. 33, pp. 73–77.

MOORE, C. B., AND H. BROWN
1962. The distribution of manganese and titanium in stony meteorites. Geochim. et Cosmochim. Acta, vol. 26, pp. 495–502.
1963. Barium in stony meteorites. Jour. Geophys. Res., vol. 68, pp. 4293–4296.
PRIOR, G. T.
1916. On the genetic relationship and classification of meteorites. Min. Mag., vol. 18, pp. 26–44.
PRIOR, G. T.
1920. The classification of meteorites. Min. Mag., vol. 19, pp. 51–63.
RAMDOHR, P.
1963. The opaque minerals in stony meteorites. Jour. Geophys. Res., vol. 68, pp. 2011–2036.
RINGWOOD, A. E.
1961. Chemical and genetic relationships among meteorites. Geochim. et Cosmochim. Acta, vol. 24, pp. 159–197.
SUESS, H. E.
1964. The Urey-Craig groups of chondrites and their states of oxidation. *Chapter 25 in* Craig, H., S. L. Miller, and G. J. Wasserburg (eds.), Isotopic and cosmic chemistry. Amsterdam, North-Holland Publishing Co., pp. 385–400.
UREY, H. C., AND H. CRAIG
1953. The composition of the stone meteorites and the origin of the meteorites. Geochim. et Cosmochim. Acta, vol. 4, pp. 36–82.
VOGT, J. R., AND W. D. EHMANN
[In press.] Silicon abundances in stony meteorites by fast neutron activation analysis. Geochim. et Cosmochim. Acta, vol. 29.
WASHINGTON, H. S.
1917. Chemical analyses of igneous rocks published from 1884 to 1913, inclusive. U. S. Geol. Surv. Prof. Paper 99, 1201 pp.